A Self-Actuating PZT Cantilever Integrated with Piezoresistor Sensor for AFM with High Speed Parallel Operation

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ABSTRACT

In this research, we studied the parasitic parameters inducing the electrical coupling between sensor and PZT actuator using simple equivalent circuit model of cantilever with piezoresistor sensor and PZT actuator. A fully integrated self-actuating PZT cantilever with a piezoresistor has been newly designed, fabricated, and characterized for high speed AFM. The fabricated PZT cantilevers provide 0.55μm/V of high tip displacement and about 5 times lower crosstalk than the previous cantilever structure. The measured resonant frequency was 73 kHz that is 100 times higher than conventional piezotube scanner. The piezotube scanner shows creep phenomena at approximately 180μm/sec of scan speed, but the fabricated self-actuating PZT cantilever has a good scanned image at 1mm/sec.

INTRODUCTION

The AFM has proven itself as a versatile instrument for science and technology since its introduction in 1986. In spite of the striking advances in the technology of the instrument, the performance is still limited by slow speeds. For scanning probe lithography (SPL) and high-density data storage applications, AFM (Atomic Force Microscopy) with high scan speed is required[1-3].

The integrated actuator improves the performance of the microscope by eliminating the need for an external z-axis actuator and the integrated sensor simplifies the operation of AFM. The integrated actuator and sensor has been worked on by many group. Suga *et al.* reported on a cantilever with two piezoelectric films of PZT, one film for the detector and actuator, the second for the reference for use in the dynamic mode[4]. Quate *et. al* developed the self-actuating ZnO cantilever integrated with a piezoresistor for high speed AFM array [1].

However, the reported ZnO and PZT self-actuating cantilever have low tip displacement due to various process problems such as co-integration between the silicon tip and the PZT actuator. Additionally, it shows the serious electrical crosstalk between the actuator and piezoresistor signals at high frequency operation [1,5]. To eliminate the unwanted electrical crosstalk, Quate *et al.* proposed the new measuring method using lock in amplifier[1] and the bottom electrode of the ZnO actuator serves as a grounding plane[5].

In this research a newly designed self-actuating PZT cantilever and array are proposed by addressing the fabrication issues. We report self-actuating PZT cantilever with an integrated piezoresistor, which have low electrical crosstalk between the PZT actuator and piezoresistor for high-speed parallel operation.

FABRICATION

The fully integrated self-actuating PZT cantilevers have been fabricated as follows. In fabricating the integrated device we started with a (100) n-type silicon on insulator(SOI) wafer with top silicon 7μm thickness. After AFM tip was formed on top silicon, a 100nm thermal oxide was grown on it to passivate the silicon and repair surface damage during ion implantation. Boron was implanted at 40keV with dose of 5×10^{14} cm^{-2} at piezoresistor region and with dose of 5×10^{15} cm^{-2} at high doping region and the wafer was subject to 1000°C 20min and 900°C 30min furnace annealing in N_2 ambient. After deposition of 240nm layer of low pressure chemically vapor-deposited (LPCVD) oxide, the bottom electrode was formed by sputtering a thin Ti adhesion layer followed by a Pt layer of 150 nm. The PZT layer with the thickness of 500 nm was formed by sol-gel process. On top of the PZT, the RuO_2 film was deposited as top electrodes. The PZT capacitor structure was patterned by using inductively coupled plasma reactive ion etching method (ICP RIE). The Au/Ti pad was formed by sputtering and lift-off process. Finally, backside silicon was selectively removed by anisotropic etching in aqueous KOH solution.

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RESULTS AND DISCUSSION

Figure 1 (a) shows 10 cantilevers array that are spaced by 200 µm for parallel operation. The SEM images of a fabricated cantilever actuators and tip are shown in Figure 1 (b). Figure 1 (c) and (d) show an integrated tip before and after PZT process integration, respectively. We found that the tips were not attacked during PZT/Pt dry etching process by plasma. All samples have a reference resistor on the substrate to reduce background noise.

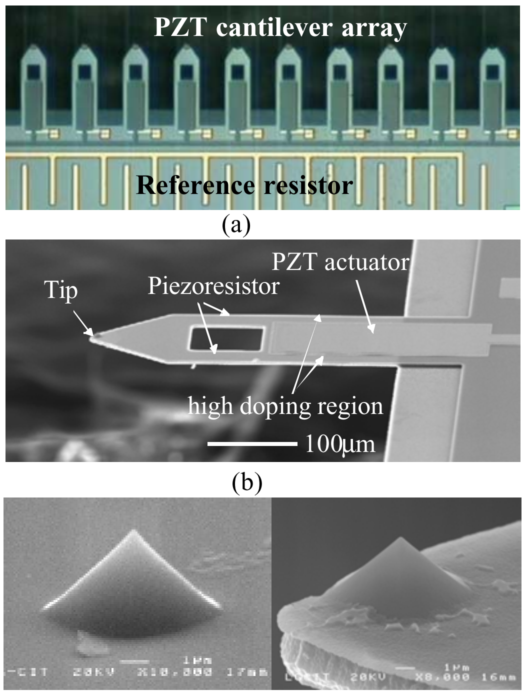

Figure 1*. SEM image of the PZT cantilever. (a) An array of Self-actuating PZT cantilevers with integrated piezoresistor. (b) image of single cantilever (c) tip image before PZT process (d) afterPZT process.*

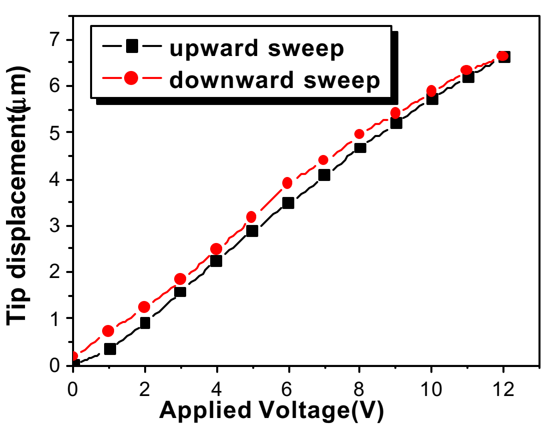

Figure 2. *Tip displacements of the fabricated self-actuating PZT cantilever*

As shown in Figure 2, the actuator provides high tip displacement of about 0.55µm per unit applied voltage but it shows a little hysteresis and non-linear behavior for large displacement. The actuator was well operated without breakdown at 20V, The operational range of the actuator is thought to be over 10µm. This operational range is much higher than that of the conventional atomic force microscopy. The measured resonant frequency is 73 kHz that is 100 times higher than conventional piezotube scanner.

To verify major parameters that are induced actuator-sensor electrical coupling at high frequency, electrical analysis is accomplished using the simple equivalent circuit shown in Figure 3.

The simple equivalent circuit does not include mechanical parameters that explain piezoresistive effect and piezoelectric effect. It can show only the actuator-sensor electrical coupling signal.

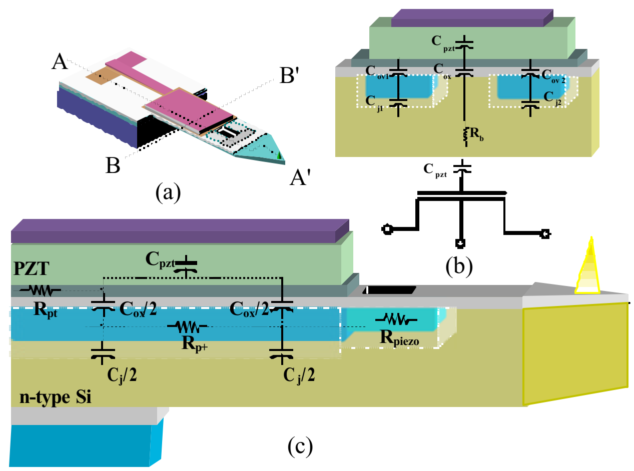

Figure 3. *(a) Schematic drawing of the Self-actuating cantilever with an integrated piezoresistor. (b) B-B' cross section of cantilever and its equivalent circuit (c) A-A' cross section of cantilever and its equivalent circuit.*

C_{pzt} and C_{ov} are PZT capacitor and overlap capacitor between the PZT bottom electrode and boron high doping region in the PZT actuator region. C_{ox} is capacitor between the PZT bottom electrode and n-type body silicon and C_j is junction capacitor between n-type body region and boron high doping region. These capacitors model is similar with p-type MOS transistor PSPICE model and C_{ox}, C_{ov} and C_j can be substituted for MOS transistor model in which related PSPICE parameters are Tox(oxide thickness), CGSO (gate-source overlap capacitance), CGDO (gate-drain overlap capacitance), CJ(Junction capacitance) and RB(Bulk resistance). R_{pt} , P_{piezo} and R_{p+} are resistor of PZT bottom electrode, the piezoresistor and resistor of boron high doping region respectively.

To explore these parasitic parameter trends, the relationship between the coupling voltage and parasitic parameters were analyzed by utilizing PSPICE simulator. The actual component values for the simple equivalent circuit made from discrete components are listed in Table I.

***Table 1.** Component values for the simple equivalent cantilever with actuator and sensor model built from discrete components.*

Component	Component parameter	value
R_{p+}	Resistance of p+ region	3kΩ
Cpzt	Capacitance of PZT	1.5nF
Tox	Oxide thickness	240nm
CGSO, CGDO	Overlap capacitance	1nF/m
CJ	Junction capacitance	50uF/m^2
CJSW	Side junction capacitance	50pF/m
R_{pt}	Resistance of PZT bottom electrode	300Ω

Figure 4 shows the piezoresistor voltage induced from PZT actuator at 30kHz PZT drive frequency as function of parasitic parameter. The resistance of PZT bottom electrode is major factor to decrease the coupling signal which is same result with ref. [5].

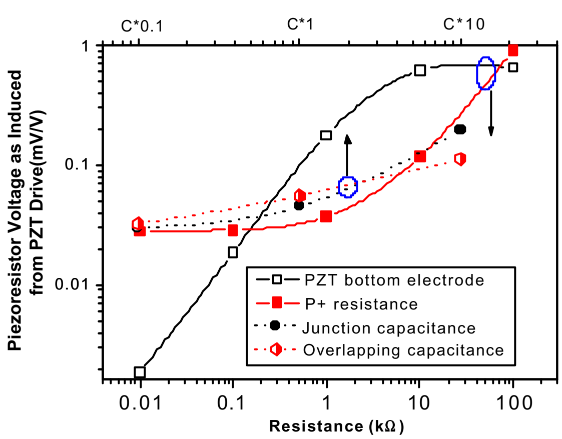

***Figure 4.** PSPICE simulation results of piezoresistor voltage as induced form PZT drive for self-actuating cantilever as functions of parasitic parameter of cantilever at 30kHz PZT drive frequency*

The second major factor is the resistance of boron high doping region, R_{p+}, this effect is dominant at high frequency region. As decreasing the resistance of R_{p+}, the coupling voltage is fast decreased at high frequency region. But as decreasing the p-n junction capacitance(C_j) or overlap capacitance(C_{ov}), the coupling voltage is slowly decreased.

For experimentally investigating the effect of parasitic parameter on electrical coupling, three types of cantilevers are fabricated. PZT actuator was designed not to overlap with piezoresistor for decreasing overlap capacitance (C_{ov}) (sample #2) in comparison with the previous structure (sample #1) shown in Figure 5.

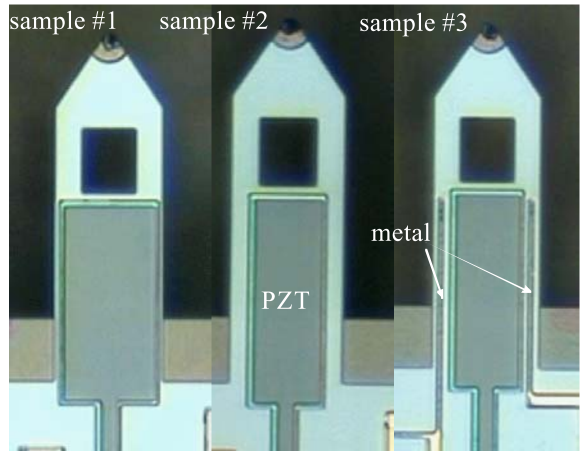

***Figure 5.** Photo images of three type cantilevers for investigating the effect of parasitic parameters on coupling voltage between PZT dirve and piezoresistor.*

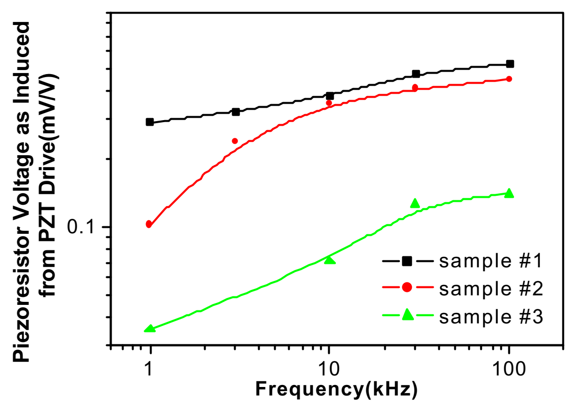

***Figure 6**. Electrical coupling voltage between the piezoresistor sensor and PZT actuator as function of PZT drive frequency for sample #1, #2 and #3.*

Figure 6 shows the electrical coupling voltage between the piezoresistor sensor and PZT actuator as function of PZT drive frequency. The measured coupling voltage of sample #2 is a little smaller than those of PZT cantilever with the previous structure (sample #2). This is because, although the cantilever of sample #2 has smaller overlap capacitance than that of sample #1, the sample #2 has similar junction capacitance with the sample #1.

These simulation and experimental results say that the junction capacitance as well as overlap capacitance is one of major parameters that induce the coupling voltage on piezoresistor.

Considering these results, we fabricated the sample #3 which has the structure that boron high doping region on the cantilever is replaced with Au/Ti metal to reduce the stray p+ resistance, p-n junction capacitance and overlap capacitance shown in Figure 5. The measured coupling voltage of sample #3 is a 5 times smaller than those of PZT cantilever with the previous structure (sample #1) as shown Figure 6.

Figure 7 shows schematic drawing of AFM system with the fabricated actuator integrated with piezoresistor for high-speed AFM measurement. The piezoresistor is placed in series with a reference resistor to form a Wheatstone bridge circuit.

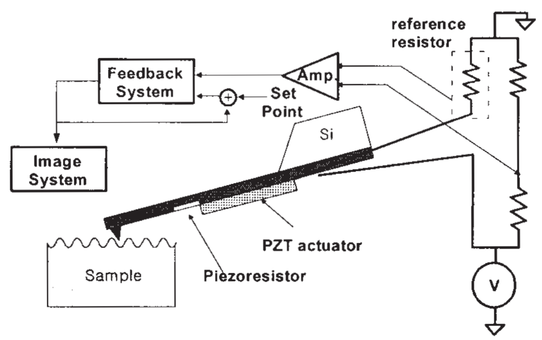

***Figure** 7. Schematic diagram of the experimental setup.*

Figure 8 shows AFM images of the standard calibration sample with 10μm period and 100 nm height, which were taken by two different operating modes.

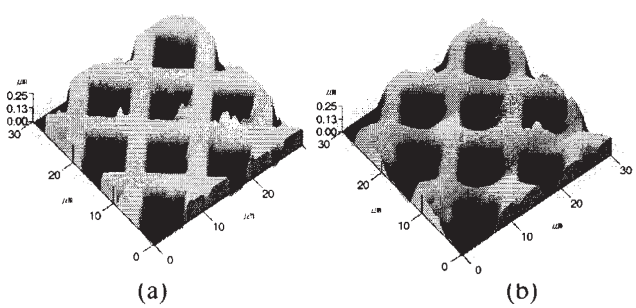

***Figure 8.** AFM images (a) using the self-actuating cantilever with an integrated piezoresistor at scan speed 1mm/s. (b) using piezotube at scan speed 180μm/s*

In first method, the bulk PZT tube scanner was used for positioning the tip in z-direction. Secondly, the self-actuating PZT cantilever was used for positioning the tip in z-direction. In case of using bulk PZT tube scanner, the creep distortion, which is logarithm drift of the height at step edge, is clearly seen even at low scan speed of 180μm/sec. This shows that the bandwidth of the tube scanner limits the scanning speed of AFM. In case of using the self-actuating PZT cantilever, we can obtain a good image at high scan speed of 1mm/sec. In this measurement, the bottleneck of the scan rate in the topographic imaging was not the property of the actuator but that of our data acquisition system.

CONCLUSION

In this research, it can be found that the junction capacitances, resistance of born high doping region, overlap capacitance as well as resistance of PZT bottom electrode are major parameters that induce the coupling voltage on piezoresistor at the self-actuating PZT cantilever with an integrated piezoresistor. We report a newly designed self-actuating PZT cantilever with an integrated piezoresistor, which have low electrical crosstalk between the PZT actuator and piezoresistor. The fabricated PZT cantilevers provide 0.55μm/V of high tip displacement and 5 times lower crosstalk than the previous cantilever structure. And the fabricated self-actuating PZT cantilever has a good scanned image at 1mm/sec.

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